

Study on survivability of 18650 Lithium-ion cells at cryogenic temperatures

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ABSTRACT

Passive survivability of Commercially-off-the-shelf 18650 lithium-ion cells is tested in a thermal scenario similar to lunar night. Survivability of cells in particular and battery pack in general is crucial for resumption of function of any lunar exploration rover after hibernation at every lunar night. The test is designed to include a batch of Commercial lithium-ion cells from different manufacturers, with different nameplate capacities and different States of Charge. The cell behaviour during the test is monitored in-situ using cell terminal voltage measurements. To comprehend the effect of exposure to extreme low temperatures some complementary tests like visual examination, dimensional measurements, Residual Gas Analysis to detect any leakage, electrical tests to appraise electrical performance and 3 dimensional x-ray computed tomography analysis to view cell internal features are carried out at ambient conditions on cells both prior-to and after soaking at low temperatures. Results indicate successful survivability of tested cells after extreme thermal soak without any significant physical or internal damage or electrical performance degradation. Variation in cell terminal voltage with temperature is a reversible change attributed to the reversible phenomenon of freezing of cell electrolyte which furthermore is confirmed through ex-situ measurement of freezing point of electrolyte extracted from tested cells.

1. Introduction

The Li-ion batteries have revolutionized the field of energy storage ever since the inception of their commercial production in early 1990s [1–5]. Today Li-ion (Lithium-ion) batteries stand-out as state-of-the-art energy storage devices. Having aptly met the massive demand for high performance portable batteries for consumer electronic goods the application of these batteries is expanding to new horizons like electric vehicles, defence and aerospace [6–8]. The application in space exploration missions pose a unique work environment for Li-ion batteries which is largely dictated by their ability to perform at lower temperatures. The low temperature operations undoubtedly depend on the ability of the cell electrolyte to support ionic conduction. The established Li-ion cell chemistry proves to be inferior for charge/discharge operations at temperatures below -20°C [9–13]. A series of hindering factors are known to contribute towards decline in cell performance at low temperatures; mainly the increased electrolyte viscosity, low ionic conductivity, sluggish Li^{+} ion desolvation and electrolyte phase transitions [10,12,16]. Recently lot of developments are brimming in where some task-centric formulations of electrolytes are being developed by fine tuning the electrolyte composition to suit tailor-made applications for operations in temperature range from -10°C to -40°C [14–19].

Every space exploration mission is unique in its design, approach and mission management and battery too as a subsystem in any of such space-craft has to cater to exceptional demands. A lunar rover mission for instance requires the battery to support the peak power load when the power generation through solar panels is in-sufficient. At all such operations during lunar day the battery pack temperature can be efficiently managed with-in the optimal window using rover's thermal management elements. The real challenge is to endure passively through the lunar night at prevailing temperatures as harsh as -180°C for duration of 336 h [20], to be able to operate in the subsequent lunar day. From a battery point of view this challenge is only one of its kind where battery is required to operate (charge or discharge) at ambient temperatures and is required to survive passively (without any load) an exposure to extremely low temperatures preferably, without any permanent loss or damage. Even though the works cited in literature addresses the ways to tackle inferior charge/discharge characteristics of Li-ion batteries by altering electrolyte composition there is hardly any information available about the passive survivability of already existing chemistry of commercialized Li-ion cells at extreme low temperatures below -150°C and the present work aims to throw some light at this ambiguity.

A Li-ion cell at open circuit conditions and at temperatures as low as

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–150 °C or beyond, might experience irreversible damages more severe than electrolyte freezing. This includes probable events like, rupturing of cell's hermetic seal, permanent distortion of electrode jelly-roll or cell swelling beyond acceptable limits. Any of such unforeseen outcomes will result in degradation of cell's electrical performance or worst of all a case of cell failure. The problems stated above are just plausible events and the survivability of a cell is required to be proven against all such odds. This paper reports the ability of a bunch of randomly selected Commercially-off-the-shelf (COTS) 18650 Li-ion cells to passively withstand this challenging thermal circumstance posed by lunar night mission scenario, through a comprehensive set of in-situ and ex-situ measurements and characterizations. This comprehensive approach involves monitoring cell terminal voltage in-situ during the thermal soak. Furthermore verifying the overall health of the cells by conducting some complementary tests at NTP (normal temperature and pressure) both prior-to and after thermal soak. The complementary tests include visual examinations to see any physical damages, dimensional measurements to establish any swelling, Residual Gas Analysis (RGA) to detect any leakage, electrical tests to appraise the electrical performance and 3 dimensional x-ray computed tomography (3D x-ray CT) scan to view the cell internal features. To make the understanding more comprehensive the test is extended to include cells from different manufacturers with different nameplate capacities and each at two extremes of State of Charge (SOC) (very low < 1% and very high > 80%).

2. Experimental details

2.1. Temperature profile for thermal soak experiment

A lunar night is equivalent to 336 h or 14 earth days. Just as the lunar night sets in, in the absence of any heat source the temperature of lunar rover components are estimated to drop sharply from an ambient value. The drop in temperature is steep during initial six hours of night and slows down as the night progresses. Temperature is estimated to stabilize after about 72 h to values below –200 °C [20]. Even though theoretically the lunar surface temperature drops below –200 °C, to simulate the same temperature conditions on ground is a practical difficulty. With liquid nitrogen (LN₂) cooled thermal cycling chambers the best achievable lower temperature is in the range of –150 °C to –170 °C. Hence the selected 18650 Li-ion cells were soaked at a best achievable lower temperature in the range –160 °C to –170 °C for duration of 336 h using a programmable LN₂ cooled thermal cycling chamber with the temperature profile stated above.

2.2. Sample selection

The experiment was designed to include a batch of three different types COTS 18650 Li-ion cells named as 'A', 'B' and 'C' with different nameplate capacities and each at two extremes of SOC. Cell 'C' is a high power cell capable of charge at 1C rate and discharge at C/2 rate. Sample cells were randomly selected from a lot. Tables 1A and 1B shows the details of the Li-ion cells selected for the study and some cell specific details.

Table 1A
COTS 18650 cells selected for low temperature soak test.

Sl No.	Cell label	Nameplate capacity (m Ah)	SOC (%)
1	Cell A1	2600	< 1
2	Cell A2	2600	> 80
3	Cell B1	2800	< 1
4	Cell B2	2800	> 80
5	Cell C1	1000	< 1
6	Cell C2	1000	> 80

Table 1B
Cell specific details giving comparison of selected cells.

Parameter	Cell A	Cell B	Cell C
Cathode active material	LiNi _{0.8} Mn _{0.1} Co _{0.1} O ₂	LiNi _{0.8} Mn _{0.1} Co _{0.1} O ₂	Li-Nickel Oxide
Anode active material	Li intercalated graphite	Li intercalated graphite	Li intercalated graphite
Electrolyte	LiPF ₆ in EMC:DEC:EC	LiPF ₆ in EMC:DEC:EC	LiPF ₆ in DEC:EC
Separator	Single layer of PE	Single layer of PE with one side HRL coat (Alumina)	Single layer of PE

Abbreviations: LiPF₆- Lithiumhexafluorophosphate, EMC – Ethylmethyl Carbonate, DEC- Diethyl Carbonate, EC-Ethylene carbonate, PE-Polyethylene, HRL-Heat Resistant Layer.

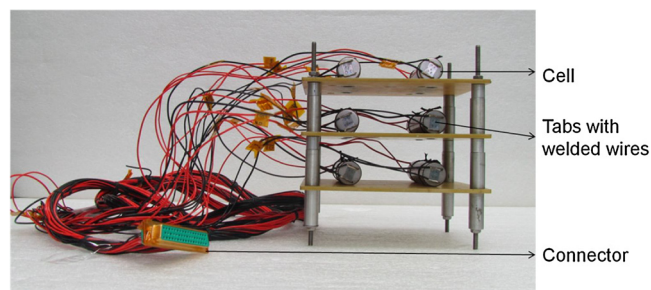


Fig. 1. The experimental setup.

2.3. Preparation of experimental setup

The cells chosen for the test were assembled together into a compact setup as shown in Fig. 1. For monitoring the cell voltages in-situ a provision was made by welding the nickel tabs with previously welded wires onto the cell terminals. The individual wires were connected to a suitable connector to interface with the electrical test system. After the completion of wiring the cells were anchored onto non-conductive base plates which later were stacked to form the test setup as shown in Fig. 1. To monitor the temperature during the progress of the soak, two thermo-couple leads were taped onto two cells in the setup. The test setup was placed inside the LN₂ cooled thermo-cycling chamber and subjected to low temperature soak with the profile close to lunar night mission scenario.

2.4. In-situ cell terminal voltage measurements

The cell terminal voltages were recorded before the start of the thermal soak test, at regular time intervals in-situ throughout the soak duration and finally after completion of the test using Data logger in auto mode with input impedance of > 1 GΩ.

2.5. Differential Scanning Calorimetry (DSC) for electrolyte freezing point determination

The electrolyte samples were extracted from tested COTS cells (at the end of all complementary tests) using an earlier developed procedure [21]. DSC measurements were carried out using instrument DSC Q100V9.6 Build 290, where the extracted electrolyte samples were first frozen by lowering the temperatures to –170 °C and later the frozen samples were gradually heated at a ramp of 5 °C/min till 25 °C. The sample heat flow was recorded as a function of temperature to distinguish the electrolyte phase transitions brought about by temperature changes. The electrolyte freezing point was determined as the temperature at which the sample showed a drastic change in heat flow.

2.6. Electrical performance evaluation

The electrical performance of the cells was judged by carrying out the standard capacity evaluation at 20 °C both prior-to and after the thermal soak.

2.6.1. Step 1: Determination Preliminary Discharge Capacity (PDC):

The cells were initially discharged at Constant Current (CC) rate, cells A1, A2, B1, B2 were discharged at C/10 rate to 3.0 V and cells C1 & C2 (being high power cells) were discharged at C/2 rate to 2.6 V. The discharge capacity (in units Ah (Ampere × h)) was recorded as PDC.

2.6.2. Step 2: Determination of End of Charge Resistance (EOC_r)

The cells were charged at Constant Current (CC) rate, cells A1, A2, B1, B2 were charged at C/10 rate and cells C1 & C2 (being high power cells) were charged at 1C rate, to 4.2 V. The input capacity (Ah_{in}) was computed product of charge current and charge duration in Ah units. The cells were opened at 4.2 V and were rested couple of hours. Open Circuit Voltage (OCV) was recorded after 2 s of termination of charge and OCV value was used to compute EOC_r, as follows,

$$EOC_r = \frac{EOCV - OCV}{\text{Charge current}}$$

Where EOC_v is End of Charge Voltage = 4.2 V.

2.6.3. Step 3: End of Discharge Resistance (EOD_r)

The cells were discharged at Constant Current (CC) rate, cells A1, A2, B1, B2 were discharged at C/10 rate to 3.0 V and cells C1 & C2 were discharged at C/2 rate to 2.6 V. The capacity delivered by the cells Ah_{out} was computed as product of discharge current and discharge duration in Ah units. The cells were opened and OCV was measured and EOD_r was computed as follows,

$$EOD_r = \frac{OCV - EODV}{\text{Discharge current}}$$

Where EOD_v is End of Discharge Voltage = 3.0 V for Cells A1,A2,B1,B2 and 2.6 V for cell C1 and C2.

The values of PDC, Ah_{in}, Ah_{out}, EOC_r and EOD_r for all the cells were recorded and tabulated. PDC and Ah_{out} indicate the capacity delivered by cells on discharge at different stages of testing. Ah_{in} is the measure of capacity put into the cells at given rates. EOC_r and EOD_r indicate the cell impedance at the end of charge and discharge, respectively.

2.7. Visual examination and dimensional measurements

All the cells both prior-to and after the low temperature soak were visually examined for any pits, scratches, dents, cracks or coloration, followed by dimensional (cell diameter measurements at three locations) using a digital calliper.

2.8. Residual Gas Analysis (RGA)

RGA was carried out to detect any electrolyte leakage from soaked cells. The experimental set-up with all six cells was placed inside RGA chamber and an ultra-high vacuum of the order 3×10^{-6} m bar was created inside the sealed chamber. The gases purged out from the chamber were characterized by feeding them to a Mass Spectrometer (MS). The plot of partial pressure of the gases with respect to their mass numbers will be displayed as RGA results. Data under similar conditions for the empty chamber prior-to and after test were also collected to nullify the background peaks in the RGA result. In case of any cell leakage the electrolyte solvent is expected to easily ooze out of the defective cell under ultra-high vacuum conditions and subsequently the solvent vapors will be detected by the Mass Spectrometer.

The current Li-ion cell chemistry employs non-aqueous electrolytes containing salt LiPF₆ dissolved in mixture of organic carbonate solvents

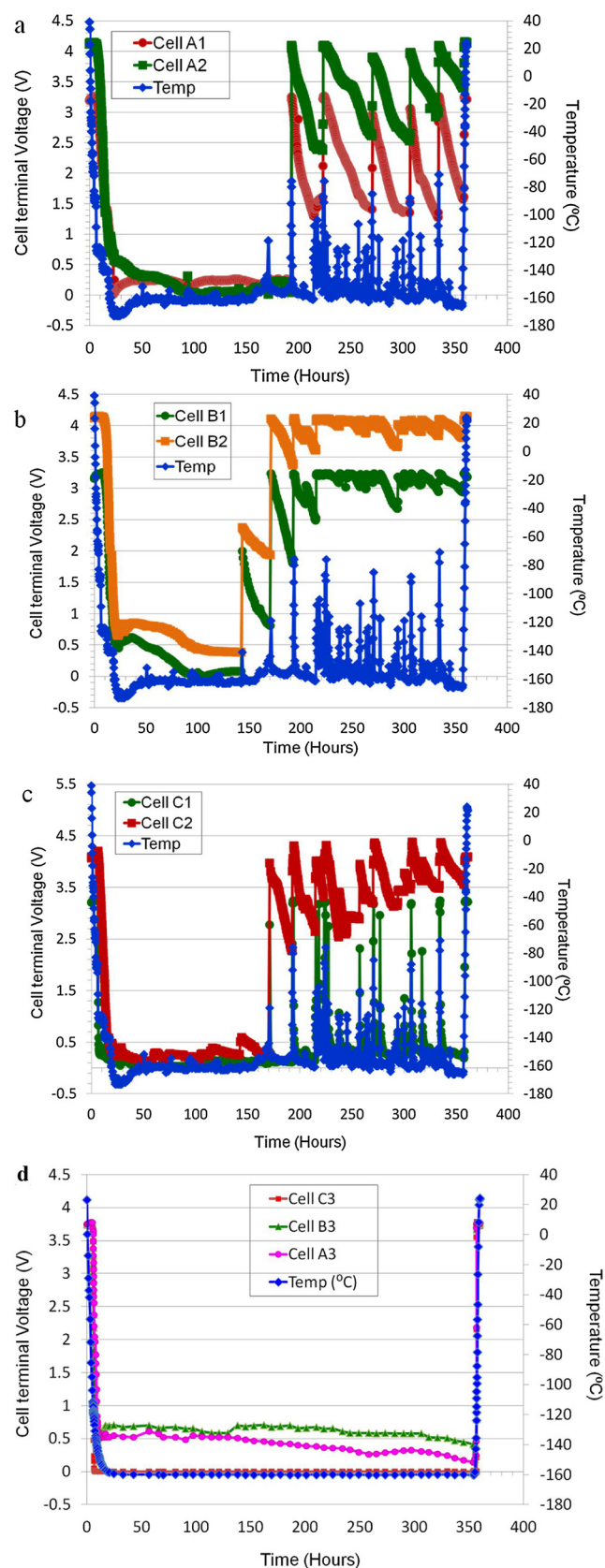


Fig. 2. The plot of variation of recorded cell terminal voltage with time and temperature for, (a) Cell A1 & Cell A2, (b) Cell B1 & Cell B2 and (c) Cell C1 & Cell C2, during thermal soak at -160°C soak for 336 h, (d) Cell A3, Cell B3 and Cell C3, during thermal soak at -160°C for 336 h inside LN₂ cooled shroud under vacuum..

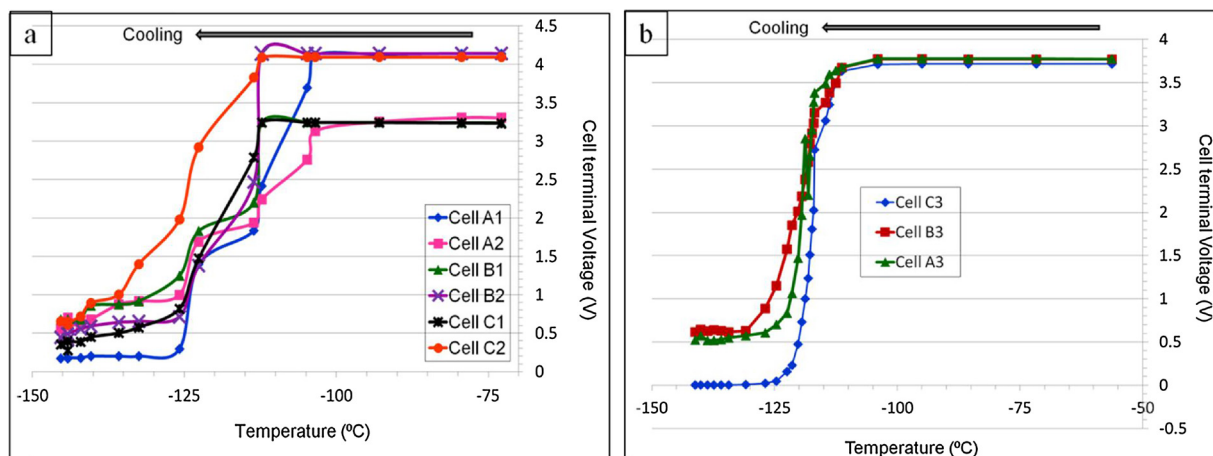


Fig. 3. Plot highlighting drastic variations in recorded cell terminal voltage in the temperature range between -100°C to -125°C during initial hours of thermal soak for (a) Cells A1-A2, B1-B2 and C1-C2 and (b) for cell A3, B3, C3.

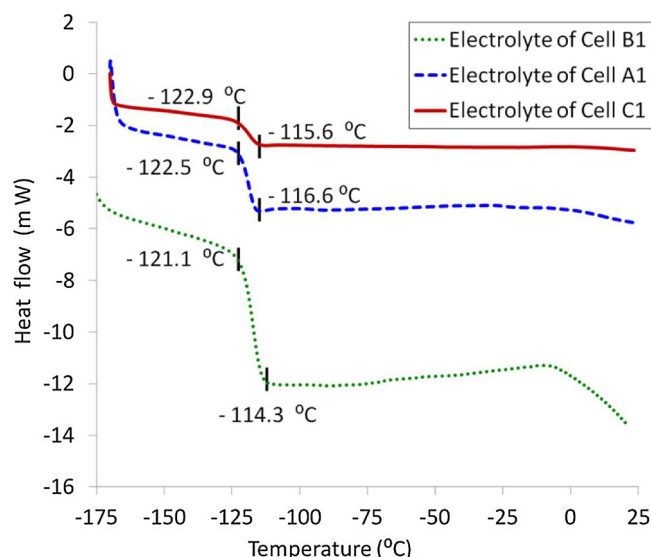


Fig. 4. DSC results showing thermal phase transitions in electrolytes extracted from Cell A1, Cell B1 and Cell C1.

like DEC (diethyl carbonate), DMC (dimethyl carbonate), EMC (ethyl methyl carbonate) as well as some cyclic carbonates like EC (ethylene carbonate), PC (propylene carbonate). The expected mass numbers in RGA result plot in case of a cell leak for the above mentioned solvents [22] (put together collectively) are; 31, 45, 57, 59, 60, 61, 62, 77, 87, 88, 90, 91 (with partial pressures exceeding 10^{-7} m bar).

2.9. Three Dimensional (3D) x-ray computed tomography (CT) analysis

3D x-ray CT analysis is a sought after non-destructive technique for visualizing and providing a 3 D perspective of any object's interiors. It is currently used to examine a wide range of materials. The use 3D x-ray CT analysis for examination of Li-ion batteries and allied materials is rather recent trend but is increasingly gaining significance [23–25]. During 3D x-ray CT analysis of present investigated cells, multiple x-ray (radiographic) images were recorded at a rate of 2301 frames per second (fps) by rotation of the cell around a central axis. These separate projections of the cells were then used to mathematically reconstruct the internal structure of the cell using system inbuilt tomographic reconstruction algorithm. This data set was then exported as 2-D stacks of images in any plane desired in order to view the internal intricate details of the cells. Due to differences in x-ray attenuating property the

cell internal materials were easily distinguished in the x-ray CT images.

3. Results and discussions

3.1. In-situ cell terminal voltage measurements

The cell terminal voltages were monitored in-situ at different time intervals throughout the test using Data logger. The Fig. 2(a–c), respectively, show the cell terminal voltage variations with time and temperature for Cells A1-A2, Cells B1-B2 and Cells C1-C2 during thermal soak at -160°C soak for 336 h.

Some facility limitations are unavoidable during long duration tests inside LN_2 cooled chambers like necessity of de-freezing of the frozen external motor by cutting-off LN_2 supply for short durations at different time intervals, as and when such an obstacle was encountered. Such actions have led to quite a number of temperature fluctuations during the test as seen evidently from plots in Fig. 2(a–c).

To overcome the temperature fluctuations experienced as described above, an additional test was carried out (at different point of time) in a more sophisticated facility by placing cells of similar lot (named Cell A3, B3, C3 but at 50% SOC) inside LN_2 cooled shroud under vacuum. The Fig. 2(d) shows the cell terminal voltage variations with time and temperature for Cells A3, Cell B3 and Cell C3 during thermal soak at -160°C soak for 336 h.

Recorded cell terminal voltages showed drastic variations in the temperature range between -100°C to -125°C and same is further elaborately shown in Fig. 3. It is evident from the above plots that in the beginning hours of low temperature soak test, the terminal voltage of all the tested cells, remained unchanged up to a temperature of -100°C . The recorded terminal voltage for all cells showed gradual drop when the temperature reduced to values in the range -100°C to -125°C . At lowest stabilization temperature of in range -160°C to -170°C all the cells showed lowest terminal voltages below 1 V. Towards the end of 336 h soak, when the temperature was brought back to ambient by heating, the recorded terminal voltages for all the cells showed gradual increase, with major changes occurring in the temperature range from -125°C to -100°C . At the end of soak recorded cell terminal voltage for all the cells were nominal same as prior to soak. Even when temperature fluctuations were encountered, all the tested cells namely; A1-A2, B1-B2 and C1-C2, have appreciably responded to every such fluctuation in temperature during soak; nominal terminal voltages were recorded when temperature rose above -100°C and as the temperature stabilized to -160°C , recorded cell terminal voltages were lower than 1.0 V.

The variation of the cell terminal voltages with temperature appears to be a completely reversible phenomenon as seen from the above

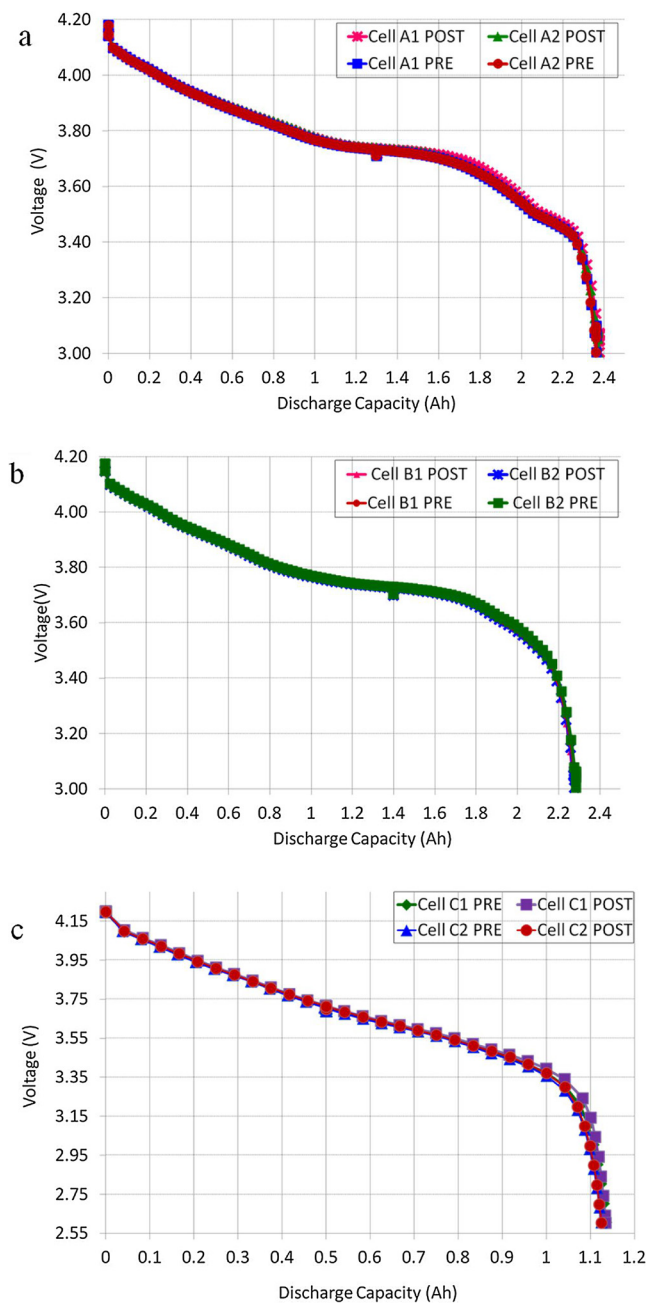


Fig. 5. Comparative discharge voltage characteristics prior-to and after thermal soak for, (a) Cell A1 and Cell A2, (b) Cell B1 & Cell B2 and (c) Cell C1 & Cell C2.

Table 2
Parameters derived from electrical performance evaluation tests.

Cell No	SOC (%)	PDC (Ah)		Ah _{in} (Ah)		EOC _r (m Ω)		Ah _{out} (Ah)		EOD _r (m Ω)	
		PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
A1	< 1	0.017	0.017	2.4253	2.4080	79	81	2.3627	2.3789	234	168
A2	> 80	2.359	2.358	2.3877	2.3813	80	81	2.3614	2.3699	211	193
B1	< 1	0.014	0.013	2.3006	2.3090	90	89	2.2807	2.2730	147	116
B2	> 80	2.247	2.247	2.2677	2.2894	92	89	2.2840	2.2646	129	119
C1	< 1	0.055	0.054	1.1850	1.2028	30	33	1.1354	1.1246	383	374
C2	> 80	1.094	1.094	1.2001	1.1796	33	31	1.1346	1.1247	386	299

SOC: State of Charge, PDC: Preliminary Discharge Capacity, Ah_{in}: Capacity put into battery in units Ah, EOC_r: End of Charge Resistance, Ah_{out}: Capacity delivered by battery in units Ah, EOD_r: End of Discharge Resistance.

Table 3

Results of dimensional measurements for the cells prior-to and after low temperature soak.

Cell No.	Cell diameter (mm)					
	Prior-to test			After test		
	Cell top	Middle	Cell bottom	Cell top	Middle	Cell bottom
A1	18.76	18.57	18.57	18.76	18.58	18.57
A2	18.75	18.62	18.63	18.76	18.64	18.64
B1	18.85	18.76	18.77	18.83	18.79	18.78
B2	18.83	18.66	18.72	18.81	18.65	18.72
C1	18.75	18.73	18.73	18.76	18.75	18.72
C2	18.71	18.64	18.67	18.71	18.66	18.68

observations. From the knowledge in literature, the most plausible explanation for such a phenomenon is change in electrolyte phase with temperature. Currently a non-aqueous system containing 1 mol of LiPF₆ salt dissolved in mixture of organic carbonate solvents is being used as electrolyte in Li-ion batteries. This electrolyte serves as a medium which facilitates the ionic conduction between the electrodes. At present different manufacturers are resorting to a variety of combinations of organic carbonate solvents which include linear carbonates like DEC, DMC, EMC as well as some cyclic carbonates like EC and PC [22]. At temperatures close to and below the freezing point of the electrolyte, severe ohmic polarization surfaces due to freezing of electrolyte, increased solvent viscosity and sluggish Li⁺ ion desolvation [10,12]. With the onset of electrolyte freezing, the cell internal impedance is expected to increase, leading to reduction in the recorded cell terminal voltages. Lowest cell terminal voltages below 1 V were recorded at temperatures well beyond the freezing point of the electrolyte mixture. Since, electrolyte freezing is completely reversible the cells tend to show the nominal terminal voltage when temperatures are brought back to ambient, at the end of the soak test.

In order to further verify the above proposed proposition the freezing point of electrolyte of all the tested cells were experimentally measured by DSC method. Fig. 4 shows the thermal phase transitions in electrolyte of Cell A1, Cell B1 and Cell C1. Similar curves have been obtained for Cells of same make; A2, B2 and C2. A distinct endothermic phase transitions in the temperature range of −114 °C to −123 °C, was seen, which most probably corresponds to freezing of cell electrolyte sample.

From the DSC results it is safe to conclude that, the drastic variations in recorded cell terminal voltage for all the tested cells, in the temperature range between −100 °C to −125 °C, as shown Fig. 3, is the consequence of onset and freezing/de-freezing of the cell electrolyte.

3.2. Electrical performance evaluation

The electrical performance of the cells both prior-to and after the thermal soak, was judged by carrying out the standard capacity

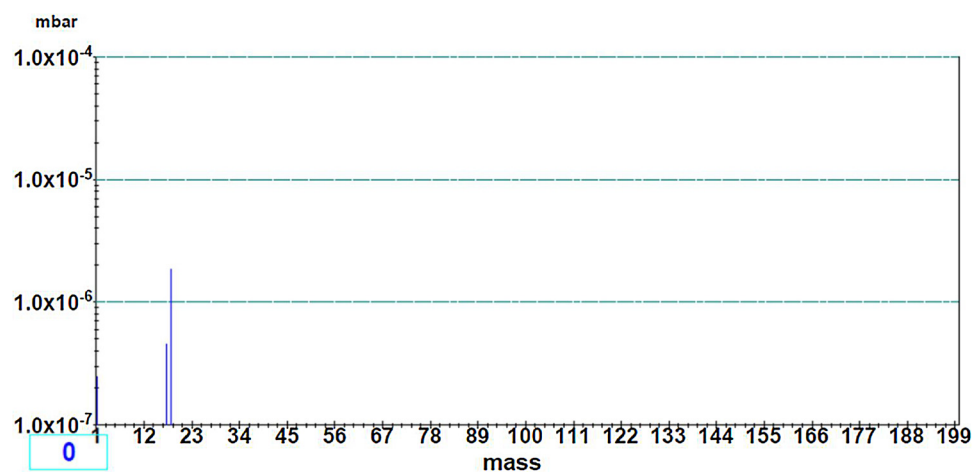


Fig. 6. The RGA results for entire cell package after temperature soak test at -160°C for 336 h.

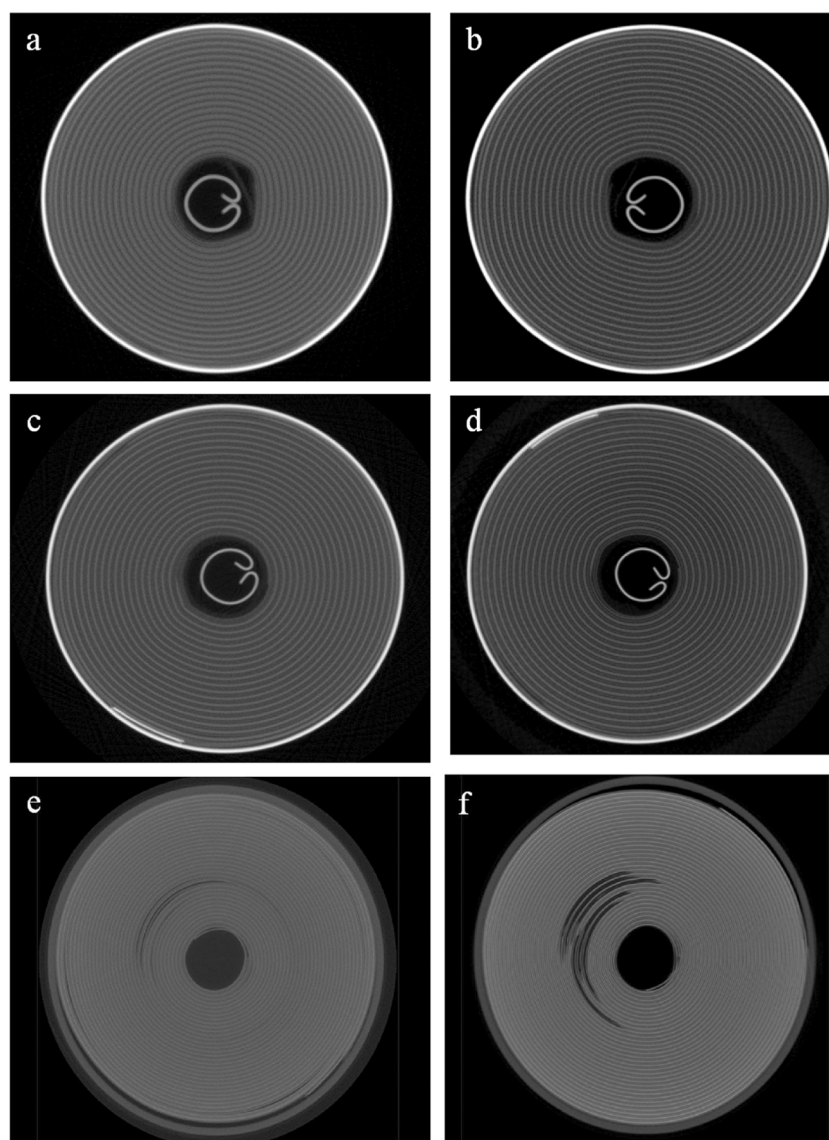


Fig. 7. Grey scale slice from 3D reconstruction tomogram in XY plane of, (a) Cell A1, (b) Cell A2, (c) Cell B1, (d) Cell B2, (e) Cell C1 and (f) Cell C2.

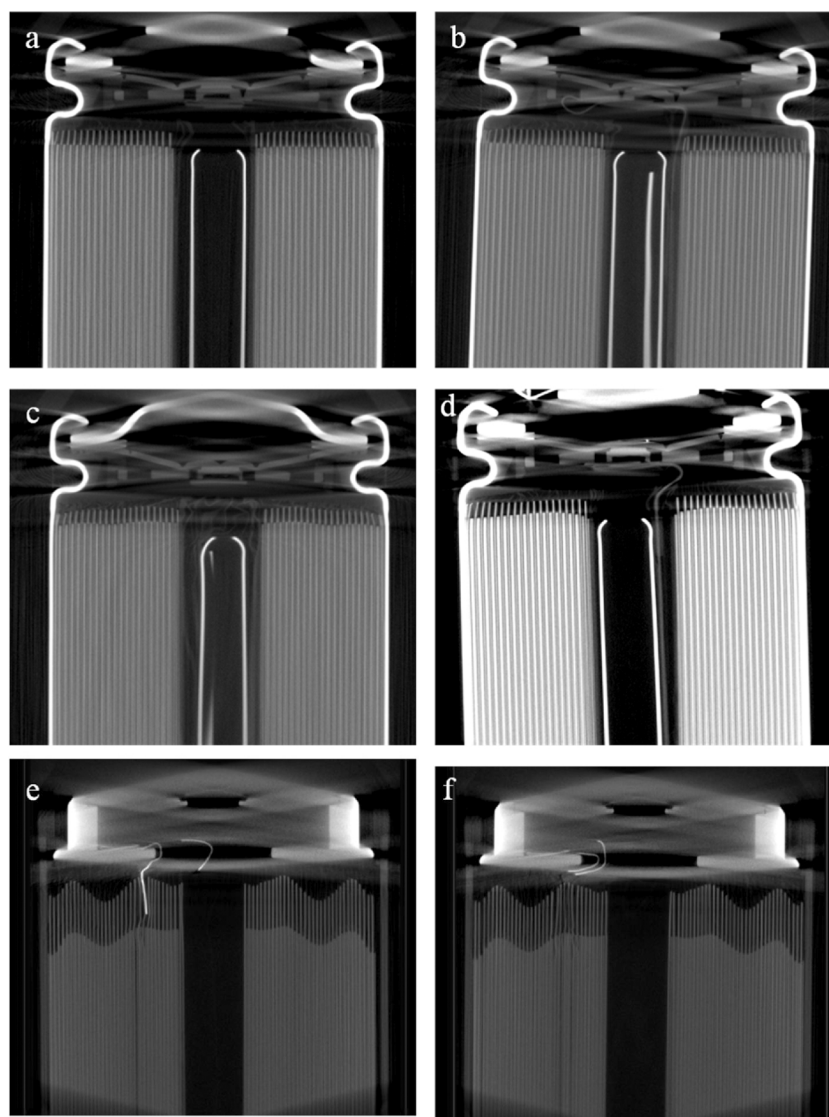


Fig. 8. Grey scale slice from 3D reconstruction tomogram in YZ plane of, (a) Cell A1, (b) Cell A2, (c) Cell B1, (d) Cell B2, (e) Cell C1 and (f) Cell C2.

evaluation at 20 °C. The comparative discharge voltage characteristic plots for Cells A1-A2, Cells B1-B2 and Cells C1-C2, during standard capacity test, are displayed in images Fig. 5(a–c), respectively.

The parameters derived from standard capacity test are tabulated together in Table 2.

The discharge voltage characteristics plots and electrical parameters listed in Table 2 do not show any degradation in electrical performance of the cells as a consequence of low temperature soak. The capacity measured just after thermal soak, PDC POST (Ah), also is excellent and is in accordance with the SOC of cells. These results further affirm the ability of the tested cells to passively survive the harsh thermal environment and still be able to deliver same performance electrically at ambient conditions.

3.3. Results of visual examination and dimensional measurements

The Table 3 show, the results of dimensional measurements for all the selected cells, both prior-to and after low temperature soak. From the results it is evident that low temperature soak do not result in any evident swelling of tested Li-ion cells.

Post the thermal soak, the insulation wrapped around the cells was removed and the bare cell case was carefully examined for any possible scratches, dents, cracks, coloration. The observations of such visual

examination indicate absolutely no damages to the cells' exteriors.

3.4. Results of residual gas analysis

The Fig. 6, show the RGA results for the entire cell package after temperature soak test at $-160\text{ }^{\circ}\text{C}$ for 336 h. The recorded RGA spectra do not show any characteristic peak for Li-ion cell electrolyte, indicating absence of any cell leakage. The two peaks at mass numbers around 18 correspond to that of water vapour. This result substantiates the robustness of hermetic seal assembly in selected 18650 cells to endure the chosen low temperature soaks test conditions.

3.5. Results of 3D x-ray CT analysis

All the cells post thermal soak were examined using 3D x-ray CT in order to non-destructively view the cell internal features and identify internal damages, if any. Figs. 7 and 8, respectively; show the grey-scale slices from 3D reconstruction tomogram of all tested cells in XY and YZ planes.

The x-ray tomographic slice images for all the tested cells do not show any significant internal damage to electrode jelly-roll. There is absolutely no evidence of any active material delamination, distortion of individual electrode layers or structural collapse of jelly-roll. This

further substantiates that a thermal soak at tested conditions for the present set of cells do not harm the structural integrity of the electrode jelly-roll. For Cell C1 and Cell C2, the inbuilt design itself involves multiple (six) tabs welded to electrode layers at intermediate positions which appear as dark patches in 3D reconstruction tomogram slice in XY plane, as seen from Fig. 7(e) and (f). This should not be misinterpreted, as the same feature is seen in all fresh cells from same manufacturer.

4. Summary and conclusions

The low temperature soak test was carried out with an intension to test the survivability of some randomly selected commercial 18650 Li-ion cells in a lunar night rover mission scenario. The 18650 cells from different manufacturers with different name plate capacities (2.6 Ah, 2.8 Ah and 1 Ah) and two extremes of SOC's (very low < 1% and very high > 80%) were selected for the study. The cell package was soaked at -160°C to -170°C for duration of 14 days. The behaviour of the cells to thermal soak was accessed using in-situ cell terminal voltage measurements. Complementary tests like, visual examination, dimensional measurements, RGA to detect any leakage, electrical tests to appraise the electrical performance and 3 D x-ray CT scan to view the cell internal features were also carried out on cells both prior-to and after soaking at low temperatures to comprehend the effect of exposure to extreme low temperatures. Recorded cell terminal voltages showed drastic variations in the temperature range between -100°C to -125°C . At stabilization temperatures of -160°C , lowest terminal voltages below 1.0 V were observed for all tested cells. The change in recorded cell terminal voltages was completely reversible, when the temperature increased to ambient values, towards the end of the test. Such a reversible change in cell terminal voltage with temperature was attributed to reversible phenomenon of freezing of cell electrolyte.

The conclusions drawn from the study are listed below,

1. All the selected COTS 18650 Li-ion cells under the tested circumstances are capable of surviving extreme low temperature soak as harsh as -160°C for 336 h or 14 days.
2. All the tested cells do not show any degradation in electrical performance due to low temperature soak.
3. The exposure to low temperatures under test conditions does not cause any physical damages, swelling, electrolyte leak or internal damage to electrode jelly-roll.
4. The cells irrespective of initial State of Charge survive low temperature exposure

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